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which tectiniques will prove most useful for problems of this size. To be prepared for the WCE both egraphic data set, it is proposed to start a congrative (comunity) effort to use these data in a sistematic way. An compariso of different existing techniques can be a first step in this direction. A number of particulants were actively interested in being involved. The data set is available to all participants, add also to other interested parties (contact C. Wunsch it MLL, or the mailing fist WOCE LNF RSDE, on telemal OMNET OCEAN). It exexpected that many other helds will be madeavailable, through collaborative effort, in appropriately guided form. These would include transient tracers, earlier the description of the properties of the wind field during the petiod, and surface color measurements. The group agreed to share data as well as model results and code. The participation of other scientists is welcomed.

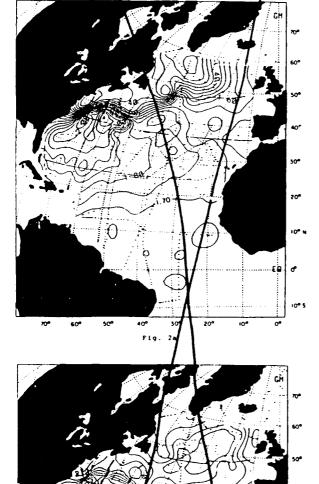
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Coupled Ocean-**Atmosphere Models**

21st International Liege Colloquium on Ocean Dynamics

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B. Edward McDonald Naval Oceanographic and Atmospheric Research Laboratory, Stennis Space Center, Miss

Global scale ocean dynamics related to El Niño-Southern Oscillation (ENSO) was the focus of the 21st International Collequium on Ocean Dynamics ENSO provides modefers a great deal of data revealing correlation between sea surface temperature (SST) anomalies and atmospheric pressure differentials in the tropics. (See Enfeld [1989] for an excellent review of the data)

tent review of the data)
The meeting was held May 8-12, 1989, at the University of Liege, Belgium More than 50 scientists attended, from Australia, Belgium, Canada, Federal Republic of Germany, France, Hungary, Italy, Japan, Netherlands, People's Republic of China, Spain, U.K., U.S., and U.S.S.R.

The 16th Colloquium, in 1984

The 1989 colloquium, in 1989

The 1989 colloquium followed one on the same theme in 1984. To give context for the 1989 meeting it is helpful to summarize the earlier one. In 1984 the 16th International Liege Colloquium on Ocean Dinamics was the first meeting to be devoted to coupled ocean-atmosphere models [Wilson]. 1985]. The motivation for the meeting was, in large part, the very strong El Niño of 1982-1983.

the very strong El Niño of 1982-1983. At the 1984 colloquium, 43 scientists presented papers. Almost 30 addressed ocean response to speficied atmospheric forcing or sixe versa. Only 2 attempted to couple oceanic and atmospheric general circulation models (GCMs). The modeling state-of-the-art at that time was not ready to attack a benchmark on the scale of the ENSO cycle. One problem that became evident in coupled GCMs was a discouraging downward climate drift in SST and air temperature. On the whole, the field of interactive ocean-atmosphere modeling in of interactive ocean-atmosphere modeling in 1984 was in its infancy, despite years of expe-rience with separately developed atmospheric and oceanic GCMs

The 21st Colloquium, in 1989

At the 1989 Liege colloquium 52 papers were presented, with about 40% addressing or using ocean-atmosphere coupling parameters. R. W. Stewart of the University of Victoria, British Columbia, Canada, opened the toria, British Columbia, Canada, opened the meeting on the optimistic note that ocean models are now approaching the point where predictions are possible. He said that political decision makers will take action based on this predictive capability and that it is incumbent on the research community to express the level of uncertainty that exists in the predictions. As the conference progressed, it became clear that his assessment of predictive capability was optimistic and his warning of uncertainty well founded.

The papers given during the first half of the meeting dealt primarily with responses o one medium to the other, with little concern for coupled interaction. The stated theme of the meeting was coupling, so the importance of the first half was to identify the relevant physics and numerics rather than present specific results.

Scientists giving papers in the secon

Scientists giving papers in the second hatf of the meeting reported varying degrees of success in modeling the ocean and atmo-sphere together. Some findings will be uted here because of their importance to the cou-pling issue. About 5 of the modeling papers addressed ENSO directly. Some promusing signs in the model results appeared in the form of eastwardly propagating SST anoma-lies with time scales of order 2 years for crossing the Pacific Ocean

Atmospheric Dynamics

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Papers on the first day dealt largely with atmospheric response to El Niño. Warm SST anomalies have two immediate effects on the atmosphere above them: increased latent heat ammiphere above them increased tatent hea flus, and increased convergence. Since atmo-spheric motion is in very delicate balance in the tropics due to the prevalence of convec-tion and the absence of geostrophic control, the warm SST anomalies quickly induce broad-scale convergence of surface air. This convergence intensifies convective updrafts, causing increased condensation and, ultimate ly, precipitation
Condensation liberates heat, which intensi-

Condensation liberates heat, which intensi-fies the surface consergence. Hence, in-creased precipitation generally follows centers of SST warming. It is the consergence of sur-face air that is primarily responsible for the increased precipitation, rather than the sim-ple increase in Street, heat flux that comes from warmer SST E. Rasmusson of the University of Maryland, College Park, described available data on ENSO and stressed the need to understand phase correlations exident in annual, brenital and lower frequency (4, 10,5 year periods) modes of atmospheric consistent. variability

The mechanism by which equatorial atmospheric responses propagate from the tropics to midlatitudes is not clear. In fact, not all model calculations propagate the response at midde can unations propagate the response at all. When propagation occurs, it does so pri-marily in response to warm anomalies. One suggested propagation mechanism involves the interaction of equatorially induced con-sergence with the jet stream. The suggestion is that the equatorial convergence interrupts the zonal pattern of the jet stream, increasing its wave number and making it more meridi-

onal in nature.

In time, increased equatorial convection In time, increased equatorial consection leads to increased counters and increased outgoing radiation. Radiation is the least understood and most complicated heat-transfer process to calculate in the atmospheric so it is the weakest component of atmospheric model. Some addiation of all and appropriate control of the con els. Since radiation plays such an important tole in tropical atmospheric motion, atmo-spheric models suffer in thie region of the

Fortunately, the other atmospheric process: es have been simulated numericalls for more than 3 decades in numerical weather prediction (NVP) models for the midlattudes. Virtualls all modern atmospheric models used for large-scale air-sea interaction research use the "primitive equations" (PE) of atmospheric motion. Such models adequatels simulate the relevant physical processes, with the excep-

Ocean Dynamics

In contrast to a long history with atmospheric PE models, orean models are relative to never. The basis is seen model currently in use for research was developed to Brown [1969]. A majority of the conference papers. about large-scale ocean simulation used one of the sariants of this model. Other models in use make playical simplications typifed by

of the variants of this model. Other models in use make plissical simplications is pified by approaches such as geostrophy, "quasi-geostrophy," lumped-parameter box ocean approaches, and one-or two laser. Laser models relate tocean estolution to horizontal motion within servicials homogenized lasers, with mosing laser boundaries describing the ocean surface and thermocline.

Ocean models respond to surface winds and to evaporation and precipitation difference. Wind stress provokes the quickest ocean responses, with time scales down to less than an hour—during passage of a storm, for example. On the other extreme, the global thermohaline circulation operates on a much longer time scale. This circulation transports the ocean's heat horizontalls and is driven by density anomalies that can be due to differential heating, evaporation and precipitation, or vertical mixing. The global thermohaline circulation time is on a decade scale.

Wind increase anomalies have two effects on the ocean; wind-driven currently and mixed-laser depending along with evaporation Mixed-laser depending, along with evaporation and precipitation, contributes to the thermohaline circulation, contributes to the thermohaline circulation, contributes to the thermohaline circulation.

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deep-ming, along with evaporation and precipitation, contributes to the thermohaline
circulation.

Fresh water input (precipitation and runoff) and evaporation contribute oppositely to
mixed-laver prise views that drive large-scale
circulation currents. Evaporation increases
mixed-laver salimity. Because saline water is
more dense than fresh, increased salimity
leads to increased convection, mixed-laver
deepening and SST cooling. Conversely,
when fresh water input exceeds evaporation,
the ocean freshens, convection is decreased
and the mixed laver shallows. Mixed-laver
deepening or shallowing sets up a horizontal
pressure gradient that manifests stief in horitonial currents. This process is the principal
component of the thermohaline circulation.
Two papers described ocean models used
to investigate thermohaline currents in the
Atlantix and the Pacific, respectively. The Atlantic study predicted an inhibiting effect on
these current that results from increased
output of the St. Lawrence River. Both stud-

output of the St. Lawrence River. Both stud-ies showed that the existence of dual steads states was plausible, suggesting the possibility that different circulation patterns may have existed in the past

Coupled Interactions

Clobal Scale Models—Discussion of model coupling began on the third day of the meeting. About half the remaining participants discussed true coupling. Due to the commit-cated nature of each individual medium's response to the other, truly roupled models re sponse to the other, truit coupled models re-quire enormus computing tenources or con-siderable simplification or both. The latter greatly compromises reality and the former is serv exponsive. Hence, all the papers on true coupling were filled with introductors qualifions such as 'simplification or 'prelimi

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In this qualifying vein, it is worthwhile highlighting some of these preliminars results relating to SST anomaly propagation. SPhilander and W. Lau of the Geophysical Fluid Dynamics Labivators (GFDL) in Princeton, N. J., found that the direction of the second of the s Princeton, N. J. found that the direction of SST anomals propagation was sensitive to the resolution of the ocean model. T. Tokioka and colleagues at the Meteorological Research Institute, in Isukuba, Japan, found eastward propagating SST anomalies with coupled 5-level atmosphere. 14-level ocean models, both having a common horizontal grid resolution of 5° × 4° K. Brayan of CFDL found SST anomalies showls propagating eastward in the Atlantic Ocean. He noted that unless a propore halance of moisture flux. eastward in the Atlantic Ocean. He noted that unless a proper balance of moisture flux between ocean and atmospheric models is maintained, the Atlantic's heat transport mechanism is impaired, leading to downward thinatological drift eventually terminating in

It appears that the models of each medium are sufficiently advanced, the interest in cou-pling is sufficiently high, and available com-puter resources are rapidly enough increasing so as to make true couplings attainable. But the present preliminary attempts make the findings still tentative.

the ginnings still tentative. Climate Drift. The most persistent of these earls findings was that both models exhibit climate drift toward evoling. Ocean and atmospheric GCMs using the PE approach solve their equations (at least in the vertical direction) by hinte difference methods. Finite differences implicitly or explicitly introduce numerical diffusion to ensure simuothness and stability of the solution. Since the ocean and stability of the solution. Since the ocean has a large reservoir of cold water beneath a

relatively shallow, warm surface laver, a nu-merical procedure that mixes this deep large cool reservoir with the shallow warm one tends to lower the surface temperature. This artificial diffusion of subsurface water into ocean models. The atmospheric radiation bal-ance problem also contributes to a cold climatological drift. When ocean and atmospheric models are coupled, this drift accelerates and eventually weakens the coupled system beyoud reality

Other Issues

Many topics other than those mentioned here were discussed at the 1989 Liege colloquium. Two papers dealt with smaller-scale model coupling, one on quasi-steads matching of ocean and aimospheris boundary lavities and the second of the secon ers, and one on hurricane dynamics.

Other usues touched on during the conference were polar se cover, global atmospheric albedo, and the greenhouse effect. Another potentially important topic not covered was potentials important topic not covered was the time and space scale mismatch between atmospheric and ocean processes. During question periods, modelers were asked for specifics on how interface conditions are han dled in light of this mismatch. Answers were died in 1881 of this mismach. Answers were short comments indicating that fluxes are in-terchanged from one to a few times per day. Apparenth, a framework for consistent flux exchange has yet to be investigated. It seems likely that the temporal and spatial scale mismatch between ocean and atmosphere will require special numerical-theoretical methods for proper treating of the interface. The rela-tive importance of these issues will, one hopes, be clarified by work in progress during the next few years

Summary and Conclusions

Similarities and differences between the first and second Liege colloquiums devoted in ocean-atmosphere coupling show the progress that has been made in the five years be gress that has been made in the five years be tween the meetings. Although both were nominally devoted to coupling, both had a minority of papers truly devoted to that top-five. The 1989 colloquium made more progress in that direction, but coupling is still a very complicated issue and most investigators pre-fer the simpler problem of one medium re-sponding to the other with no feedback.

sponding to the other with no teedback. Despite this preference, a number of indicators point in an optimistic direction for coupled modeling. In 1984 the community was hardly ready to attempt serious interactive coupling of GCMs because of limited computer resources and few proven models. Independent ocean and atmospheric modeling has made considerable progress over the past 5 years. Computer resources are considerably greater now than 5 years ago, and excellent global models exist for coupled experimentation. ntation

A few anecdotes help capture of the collo quium. Referring to the history of uncoupled models, one speaker pointed out "impropricties" of "topless oceans and "bottomless at mospheres." Another speaker compared the ocean-atmosphere interaction to a marriage occan-amosphere interaction to a marriage. The parties to this marriage exchange heat and have periods of elevated stress. At times one member of the partinership is slave to the other, and at other times forces the other into action. Each member of the partinership has its own personality; the atmosphere is impetuous, the occan rather reserved.

Another stocker pointed dut the need for

Another speaker pointed out the need for reliable component models with a profound

observation when two had models are couobservation—when two had mostes are cou-pled, it is possible to get a had result. A more serious summars was given by S. Ine-son of the Meteorological Office, Bracknell, U.K., when he said. Coupled modeling is seen difficult, but we are making progress Because ocean atmosphere model coupling is a relatively new and uncharted field, ambi-

is a relatively new and uncharted held ambi-tious modeling efforts are still in shake down phases. Modelers are generally moving to-ward qualitative reasonability of results with quantitative accuracy of predictions ver to be determined. In comparison with develop-ments in the component modeling area, time conclusions and new insights in coupled occasionmenter, modeling area, times conclusions and new insights in coupled ocean-atmosphere modeling are clusive. Within the component models, physics improvement seems to be required in atmospheric radiation simulations, and improved numerical diffusion from the ocean models. Larger computers will be required to allow both models to be run in sufficient time and space resolution to include all the relevant processes. Since this latter suggestion contains an element of "brute force," there is an indication of need for more theoretical work on consistent models could be allowed to the consistent model coupling allowing for dispage. consistent model coupling allowing for disparate time and space scales of the ocean and atmosphere

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